Design of a High Altitude Fixed Wing Mini UAV – Aerodynamic Challenges

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This paper attempts to bring out the challenges associated with the design of a high altitude mini UAV especially from the aerodynamics perspective. The mini UAV under consideration is a 2 kg class conventional, high wing and T-Tail configuration. A comparative study of various high lift airfoils has been done to illustrate that the selection of a suitable airfoil for high altitude applications is indeed an important part of the design activity and it shows that the wing loading of a UAV designed for high altitudes does not depend on the changes in air density alone. The chosen high lift low Reynolds number airfoil is found to have a minor effect on the aerodynamic parameters (C_l and C_d) with changes in Reynolds number. This paper also addresses the performance variation due to operation at off design condition such as at sea level.

Nomenclature

A	=	aspect ratio
e	=	Oswald's efficiency factor
C_L	=	coefficient of lift
C_D	=	coefficient of drag
C_M	=	coefficient of pitching moment
W/S	=	wing loading
T/W	=	thrust loading
P	=	total power consumption
η	=	propulsive efficiency

I. Introduction

A wide variety of unmanned air vehicles varying in their shape, size and configuration have been developed by government/private organizations across the world. These typically vary in terms of flight speed, operational altitude and endurance depending on the mission requirements. Historically, UAVs were designed as simple drones, but autonomous control is now increasingly being employed. UAVs come in two varieties: some are controlled from a remote location, and others fly autonomously based on pre-programmed flight paths using more complex dynamic automation systems.

The AeroVironment Pointer (2.7 m) mini UAV was amongst the first generation of mini UAVs in early 90s' designed as a tactical reconnaissance vehicle for military and law enforcement applications in confined areas. When it was released, a package of 2 airplanes and a ground station had a cost which was a fraction of that of larger UAVs that reached millions of dollars. With increased awareness of these types of UAVs, it became clear that mini UAVs had the potential to reach a much wider customer base in very little time of development.

Survey [1] showed that depending on the function, the vehicles can be classified broadly into six categories namely, Target and decoy, Reconnaissance, Combat, Logistics, Research and development, Civil and Commercial UAVs. It is also observed that there is no vehicle in the weight class of proposed mini UAV. So vehicles are looked with takeoff weights in the vicinity of the proposed weight. Survey showed that there are six countries having UAVs in the weight class 1.70 to 4.0 kg. Limited geometrical and performance parameters of these UAVs are available in the open literature. The specification of the proposed mini UAV is detailed in the appendix.

II. Design Challenges for High Altitude Flight

The Slybird mini UAV, as it is called has been designed for a maximum launch altitude of 4500 m above sea level, where temperatures are low. As per the international standard atmosphere table, at 4500 m the temperature will be -14^0 C where the density and viscosity decrease by about 37 % and 8 % respectively compared to values at sea level conditions. So the design of airframe and its subsystems including the material used for fabrication has to take into consideration the changes in density and temperature.

One of the critical parameters that dictate the aerodynamic design of the vehicle is the operating Reynolds number. Due to the decrease in the density and viscosity, the operating Reynolds number will reduce by 31 % compared to sea level conditions. The change in the maximum lift to drag ratios for majority of the airfoils is very sensitive to the changes in Reynolds number in the range of 80,000 - 140,000. An appropriate chord length has to be finalized for the airfoil to be chosen to keep the operating Reynolds number beyond 150,000. To satisfy this requirement, it is proposed to have the operational Reynolds number in the range of 150,000 - 200,000 and chose an airfoil to have the maximum lift to drag ratios around this range of Reynolds number.

Slybird mini UAV has been designed for flight at an altitude of 4500 m above sea level. In case of flight operations at sea level, the atmospheric density and viscosity will be higher and the operating Reynolds number for cruise condition will be higher resulting in different aerodynamic characteristics. For cruise speed of 12m/s, Reynolds number based on mean aerodynamic chord of 0.278 m will be 228,000 at sea level and for high altitude it is 158,000. The aerodynamic characteristics at these Reynolds number is computed and shown in Figure 1. As seen there is no change in the lift and slight change in the drag and this result in a slight decrease in the lift to drag ratio at higher Reynolds numbers. Due to this, there will be a change in the performance in terms of endurance (as the drag is slightly higher).

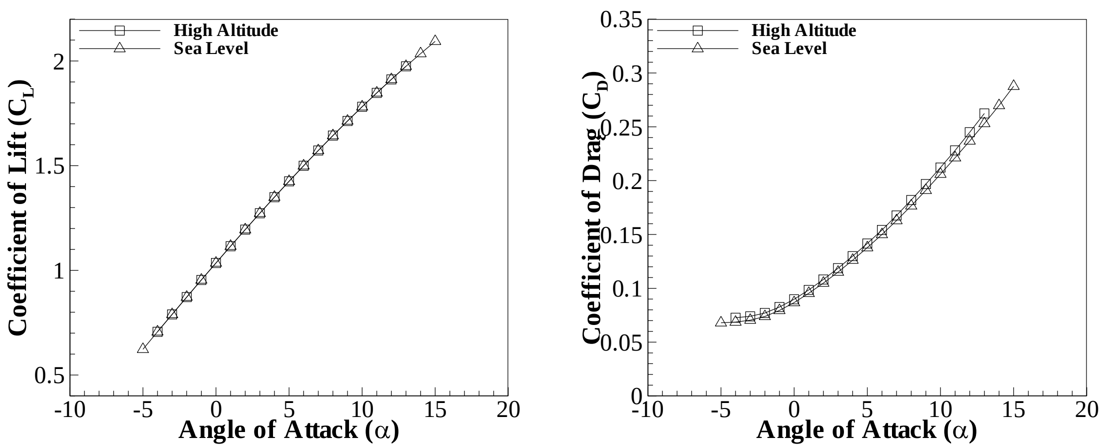


Figure 1 Comparison of Coefficient of Lift & Drag (C_L & C_D *Vs.* Alpha) at Different Reynolds Numbers

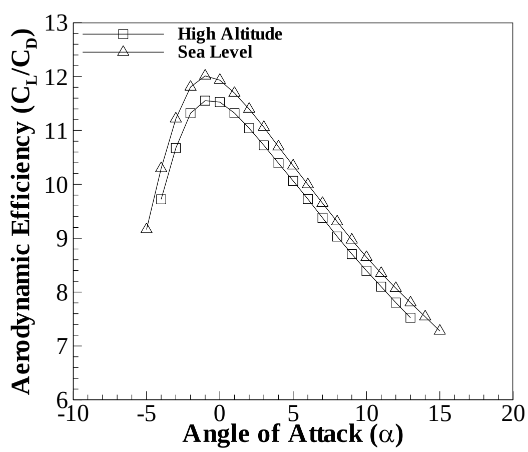


Figure 2 Comparison of Aerodynamic Efficiency (C_L/C_D *Vs.* Alpha) at Different Reynolds Numbers

Selection of propulsion system consisting of a combination of propeller, motor, and battery has to be looked at from the point of view of reliability of operation at low temperatures. As the density is reduced by 36 %, the mass flow rate through the propeller for a given speed (RPM) decreases, and the thrust produced may decrease and also condensation on the propeller blades due to high velocity on the propeller blades may lead to lower efficiency of the propeller. The motor and battery chosen should be able to operate at lower temperatures. Care must also be taken to see that other subsystems like sensors, video link, and telemetry link are operational at low temperatures. Composite material chosen for fabrication should retain its strength and shape for long duration of operation and for repeated flight operations.

III. Methodology Adopted

This section highlights the design approach followed for the development of Slybird mini UAV. The processes followed for the development is as follows:

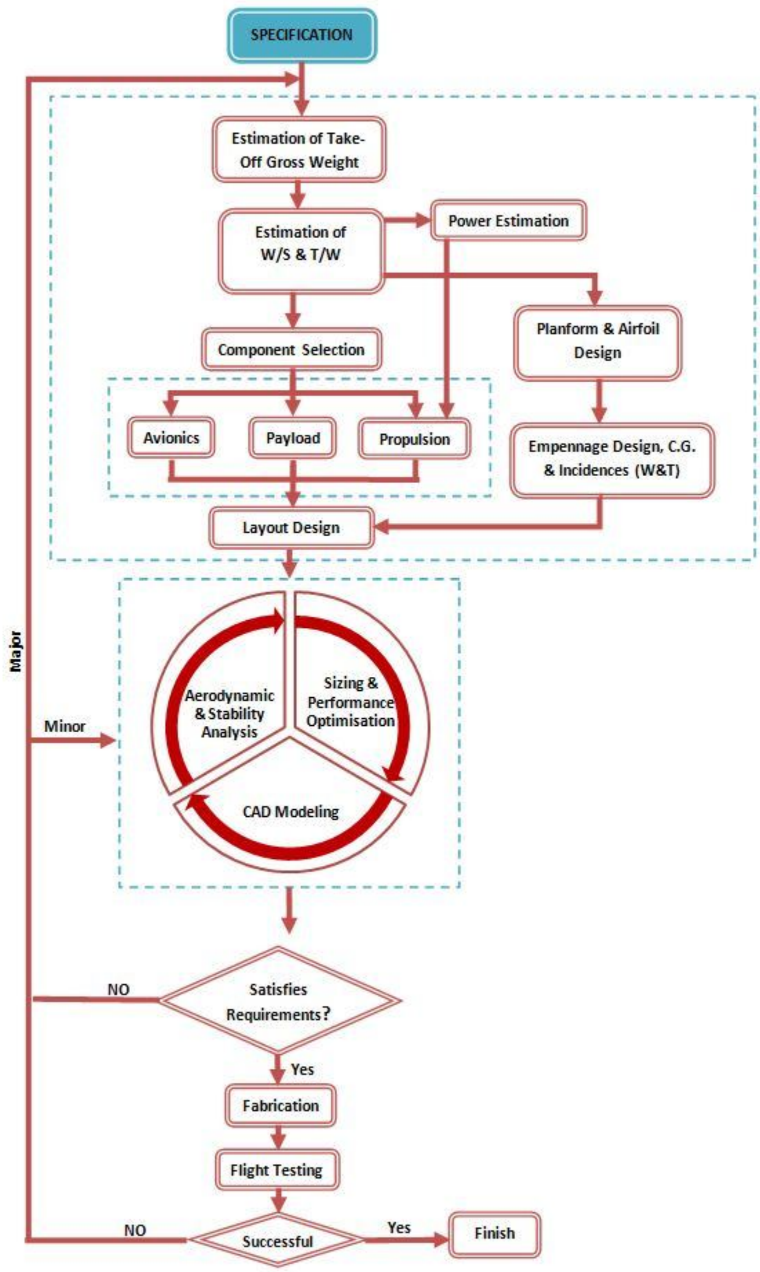


Figure 3 Design Process followed for the development of mini UAVs

To start with, a preliminary estimate of the weight of the aircraft and all its subsystems is made to begin the geometry sizing. The weight estimation according to various fixed components for propulsion, payloads, avionics, airframe, communication systems and actuators are as shown in a pie chart (Figure 4) below:

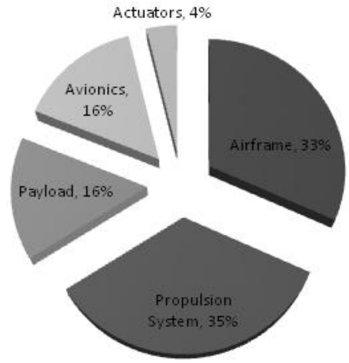


Figure 4 Weight breakup of fixed subsystems

IV. Sizing and Aerodynamic Analysis

To estimate the wing parameters, a value for wing loading (W/S) is typically the first to be estimated. This is one of the most important parameters that not only decide the wing parameters but also plays an important role in the performance estimation of the aircraft. Wing loading was calculated based on the criterion for stall speed, cruise speed and turn rate respectively. The equation for turn rate inevitably gives us the value of thrust loading at cruise. Once the wing loading and thrust loading were calculated, geometrical details were finalized based on a suitable value of wing aspect ratio and taper ratio. Aerodynamically, it is desirable to have a large aspect ratio (A). However, we settled at an optimal value of 6.0 as this is not too far from the 2D lift curve slope and does not call for an extensive strategy for structural design. The taper ratio (λ) is a geometric parameter that is roughly the same for all the aircrafts in the dataset. We choose an average value of 0.5 for λ.

Wing loadings obtained from various criterions are summarized as follows:

	Stall Speed (10 m/s)	Cruise Speed (12 m/s)
W/S	81.585 N/m^2	58.275 N/m^2

	Cruise	Turn Radius (Same as Cruise)	Climb at 3 m/s	Bank at 60^o
T/W	0.1228	0.1228	0.38	0.2456

Dihedral of the wing affects the lateral stability of the airplane. Since there does not exist a unique method to determine an effective dihedral angle that would satisfy all the requirements of lateral stability of the airplane, we rely on a thumb rule for sailplanes that typically use 3 to 5 degrees of dihedral. Starting from two third of the wing span upto the tip, a dihedral angle of 10 degrees is given making the equivalent dihedral angle of the wing equal to 3.67 degrees. The wing and tail incidences are respectively the angles made by the airfoil chord lines and the fuselage reference line. Incidences are employed primarily to optimize C_L during cruise and to have suitable pitching moment characteristics of the airplane. Ideally, for a conventional airplane, the value of $C_{m\alpha}$ should always be negative with a positive value of C_{mo}.

To calculate the absolute values of the wing and tail incidences we have approached using force and moment balance of the airplane. The analytical values of the incidences for wing and tail planes are 3^o and -2.5^o with respect to FRL respectively.

The design of fuselage should ideally resemble that of a slender body due to aerodynamic considerations. But in this case, the dominant factor governing the fuselage design is the need to house the aircraft fixed components such as, the camera (payload), battery packs, motor, propeller etc. Further it has to hold the wing and empennage in place. A suitable shape for fuselage can be rectangular with filleted edges up to a certain distance and a tail boom thereafter to hold the empennage. For ease of fabrication (seamless construction), the fuselage shape has been kept cylindrical. Taking the vertical dimensions of the fixed components into consideration, the diameter required for the fuselage comes to around 120 mm. A suitable hatch back is also provided for the ease of operation of the propeller. The fuselage is connected to the tail through a boom of circular cross section. The aircraft is designed as a pusher configuration to allow cleaner aerodynamics over the wings and to predict the design calculations accurately. A prototype made of carbon fiber and Kevlar is as shown in Figure 5.

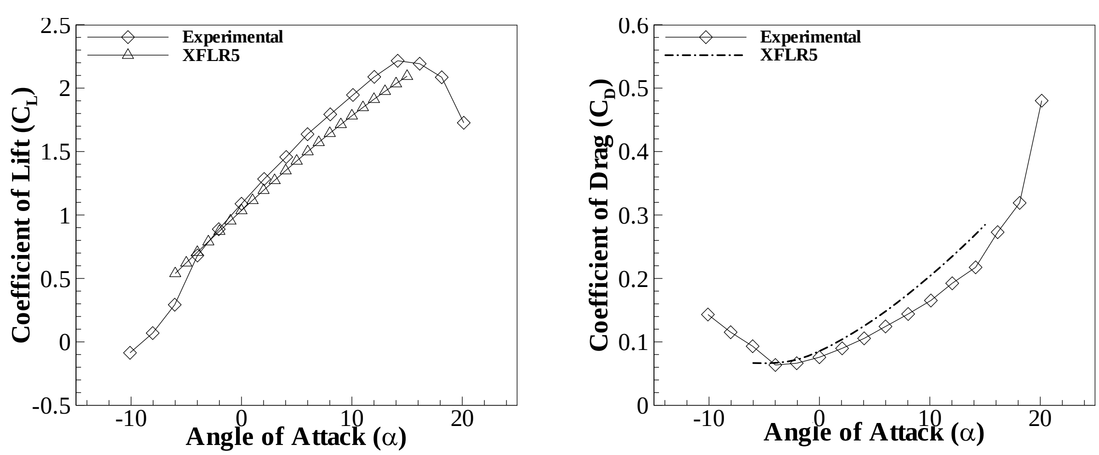
Figure 5 Prototype of Slybird mini UAV

A. Wind Tunnel Test

A full scale (1:1) model for Slybird mini UAV has been tested at ARDC Low Speed Wind Tunnel at the Hindustan Aeronautics Limited (HAL) [11]. The model and the mounting components were fabricated by NAL and subsequently supplied to HAL for testing. ARDC wind tunnel is a closed circuit type and has an octagonal test section of size of 2.74 m x 1.83 m and can conduct tests in the range of 5 – 50 m/s. Testing for un- propelled models were done and were conducted at a free stream velocity of 12 m/s, 15 m/s and 20 m/s for incidences ranging from -10^o to +20^o in steps of 4^o. The Beta sweep was in the range of -15^o to +15^o in steps of 5^o. The aileron deflection was in the range of -15^o to +15^o in step of 5^o. The elevator and rudder deflections were also in the range of -20^o to +20^o in step of 5^o.

As seen in the following plots (Figure 6), the maximum coefficient of lift (C_{Lmax}) is very close to the corresponding 2D value which is advantageous for a surveillance mini UAV and can provide a very low value of the stall speeds. Figure 1 shows a fairly linear trend for the variation in the coefficient of lift with angle of attack. C_{Lo} and $C_{L\alpha}$ are found to be quite high at 1.07 and 0.1/deg respectively. Variation in the coefficient of drag with AoA is shown in Figure 6(2). Minimum drag occurs at around -3 deg. The steepest drag rise is observed at 12 m/s when the aircraft approaches the stall angle of attack of 14 degrees. At the lower end of the range, the drag coefficient starts to rise as the AoA is lowered further to the stall angle of -4 degrees. Figure 6(3) shows the coefficient of pitching moment measured about the L.E. of the root chord of the wing. The slope of the variation in C_m with alpha is also quite large indicating a very high static stability of the airframe. The aircraft is trimmed at around -4 deg AoA.

Lift and drag computed from XFLR5 compares well with the wind tunnel experiments at lower values of angle of attack. This also gives rise to a large change in the aerodynamic efficiency of the aircraft.



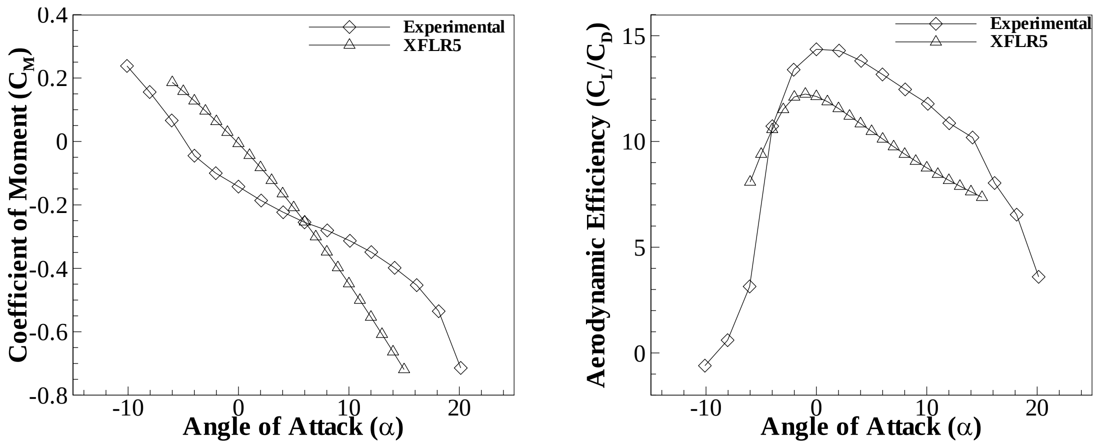


Figure 6 Validation of XFLR5 results with wind tunnel experiments on a 1:1 scale Slybird model

B. Point Performance

Thrust and power required to cruise and climb are the most important performance parameters for the mini UAV of this class. These are represented by the following equation and are plotted in Figure 7.

$$T = D = \frac{1}{2}\rho V^2 S C_{Do} + \left(\frac{2kW^2}{\rho V^2 S}\right)$$

$$P_R = DV = \frac{1}{2}\rho V^3 S C_{Do} + \left(\frac{2kW^2}{\rho V S}\right)$$

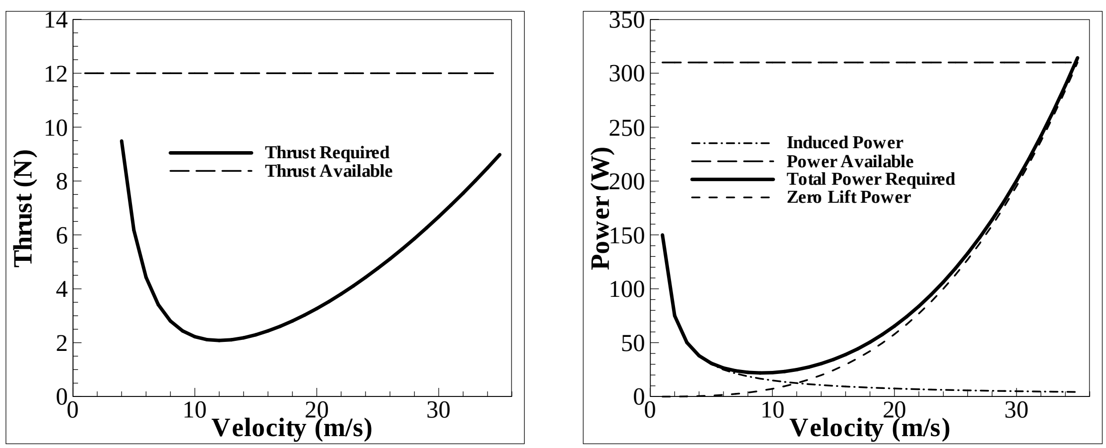


Figure 7 Thrust and Power required to cruise at 12 m/s at high altitudes.

C. Performance at Off-Design Conditions

Variation in vehicle weight usually occurs due to unforeseen problem that may arise during fabrication. Many times the vehicle components require stiffness at the joints and increased thickness of materials at certain places leads to increase in weight of the vehicle. Apart from this, during flight tests it may be proposed to add a new payload which weighs more than the old payload and different autopilot or antenna which may lead to additional weight of the vehicle. The designed configuration has to be verified for its performance due to the increase in weight that may likely occur due to these factors. A sensitivity analysis is made with weight as a variation. Figure 8 shows that to carry an all up weight of 4.5 kg, which is about 200% more than the designed take-off weight, the mini UAV has to cruise at about 15 m/s keeping coefficient of lift at cruise as 1.0.

Similar computations for cruise at sea level shows that to cruise at 12m/s, the lift coefficient decrease to 0.66 for design weight of 2.57kg (Figure 8(2)).

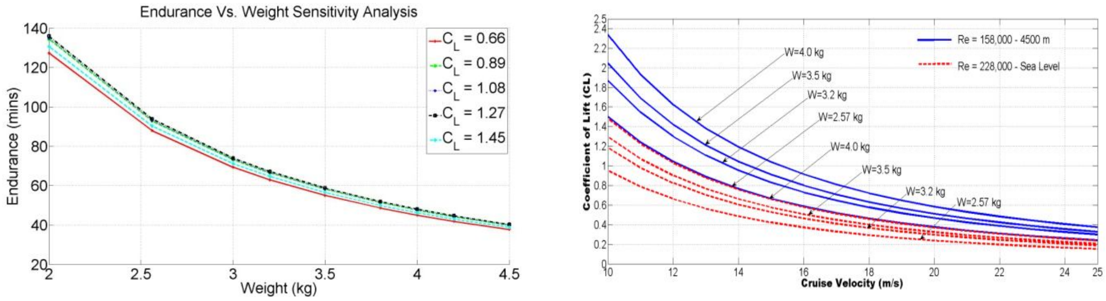


Figure 8 Weight Sensitivity Analysis for Slybird at Sea Level

V. Conclusion

The configuration of a fixed wing unmanned air vehicle with a maximum takeoff weight of 2.57kg has been designed for operation at an attitude of 4500m above sea level. The design is initiated with a wing loading of 58.275 and wing aspect ratio of 6.0. After obtaining the preliminary geometry of the wing, empennage and fuselage and using XFLR5 freeware, the aerodynamic characteristics of the configuration were computed. With the aerodynamic data thus obtained, the wing loadings are recomputed from the consideration of stall, cruise and loiter endurance and from this, optimized wing loading for cruise is taken into consideration for refining the geometry of the configuration. A layout of the configuration with all the components housed inside the fuselage is done. The refined configuration is further investigated for its static and dynamic stability and its performance is estimated for both glide and climb condition. Thrust to weight ratio for climb is determined and to meet this ratio, an appropriate propulsion system is chosen. After the fabrication and integration of the propulsion system and the other components, flight tests were carried out at Leh, Ladakh. Flight trials show the configuration was stable and maximum endurance of 60 minutes was observed. A sensitivity analysis with weight of the vehicle as a variant is carried out and this shows that the present configuration can have a stable flight with a maximum takeoff weight of upto 4.0Kg.

Appendix

Parameters	At 4500 m	At Sea Level
Endurance	60 mins	90 mins
Glide Angle	4.7	4.0
Glide Range	1.22 km	1.44 km
Stall Angle	14^0	14^0
Stall Speed	10 m/s	8.5 m/s
Turn Radius	5.88 m	4.25 m
Turn Rate	1.7 rad/sec	2 rad/sec
Maximum Speed	30 m/s	35 m/s

Parameters	Existing/Achieved
Wing span (m)	1.61
Maximum Take-Off Weight (kg)	2.57 – 4.00
Operating altitude (m)	4500
Speed range (m/s)	10-25
Cruise Speed (m/s)	12-20
Endurance (min)	> 60
Telemetry Range (km)	10.0

Acknowledgments

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